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Review Article

Flat Plate Solar Collectors and Applications: A Review

Bande, Y. M.* and Mariah, N. A.

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

In this study, various methods and applications of flat plate solar collectors are discussed and pictorial representations are presented. Low temperature applications of flat plate collectors are identified in solar cooking, solar water heating, space and air heating, industrial heating plants and in agricultural produce drying processes. Basic equations, as presented by many researchers in the performances of flat plate collectors, are also presented. The review discusses the analysis of losses from flat plate collectors towards obtaining the overall heat loss coefficient which indicate the performance of flat plate collectors.

Keywords: Flat plate collectors, air heating, water heating, heating and cooling of buildings, solar drying

INTRODUCTION

Flat plate collectors are designed to collect solar radiation at high frequencies. This radiation falls on its black painted surface and converts the radiation into heat energy. They are placed in relation to the latitude and longitude of a location to obtain the best output from them. Flat plate collectors are described as the most important in solar energy applications that involve heating or cooling, irrespective of the end-use application. Sparrow *et al*. (1977) concluded that the performance of the flat plate collector is dependent on the losses from the bottom, top and sides of the collector. Therefore, to calculate heat loss from the collector to its surrounding is crucial for the design performance of the solar collectors as presented by Akhtar and Mullick (1999). Hence, the effectiveness of the collector is the difference between the incident radiation and the amount of energy loss from the collector from any of the exits since the heat loss can be evaluated with the useful energy, if the overall heat loss coefficient is known.

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Email addresses:
Bande, Y. M. (ymbande@yahoo.com),
Mariah, N. A. (mariah@upm.edu.my)
*Corresponding Author

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In analyzing of performance of these collectors, the overall heat loss coefficient is assumed constant per location and its configuration. This explains why conventional collectors, where heat transfer coefficients are considered constant, the flat plate collectors are considered linear (Cooper *et al.,* 1981). Thus, flat plate collectors find applications most commonly in low temperature applications such as water heating, solar cooking, agricultural produce drying, solar distillation, desalination processes, domestic ovens, industrial process heating and even space heating or cooling and heating of buildings.

For high temperature applications, solar flat plate collectors are "modified" by enhancing "concentrated" solar radiation beams, and using additional reflectors directed towards the collectors to tremendously increase the temperature generation of collectors. This has found applications in solar reflectors and solar concentric furnaces. The applications of flat plate collectors are therefore many and the application of which is directly related to end use. Goyal and Tiwari (1999) experimented on the reverse flat plate absorber for the drying of agricultural produce. In their findings, the reverse flat plate absorber offered a better and more uniform drying since the produce was not exposed to direct contact with the sun.

Several authors have also reviewed works on flat plate collectors. However, no published work has been done on the applications of plate collectors so far. Thus, the present review is specifically on flat plate solar collectors and their applications. In particular, the review focuses on heating, cooling, drying, furnace, pumping, thermal power generation, cooking and solar pond applications.

FLAT PLATE COLLECTORS

The performance of solar energy flat plate collector is subject to the amount of heat energy losses from its surface as proposed by Francey and Papaionnou (1985). Computation of these losses is usually cumbersome. Hottel and Woertz (1942) suggested an empirical expression for calculating Ut, the top loss coefficient. This has undergone several modifications by researchers' worldwide. The useful energy possibly obtainable from a solar collector is the difference between the solar energy incident on the collector and the amount of heat lost from the collector. Garg *et al.* (1983) concluded that the overall heat-loss coefficient, U_l, is a function of many parameters such as material properties of the collector, ambient conditions, position of the collector and its configurations, wind speed and direction, and absorber temperature.

Calculation to obtain heat losses from collectors to the surrounding area is of vital importance for the design or simulation of their performance. It is evaluated by considering convection and radiation losses from the absorber plate in the upward direction (Soddah *et al*., 1982).

Two methods of calculating U_t are generally identified as:

- Approximate method
- Numerical methods

Approximate solution has however been accepted much by researchers in solar thermal systems. Hottel and Woertz (1942) first proposed the empirical equation estimating U_t of the flat plate collectors. Later, the empirical equation that gives good correlation with emmittance at absorber plate was modified by Klein (1975). Solar flat collectors are designed to gain useful heat energy from the incident solar insolation. Several types of solar flat collectors can be developed, and these may include flat-plate or concentrating types. The applications of the generated heat energy suggest the type to be used, whereby the concentrating type found to generate more heat energy than the flat plate type. In crop drying, for example, a simple flat-plate solar collector can generate just enough heat energy to attain equilibrium moisture content for drying.

A simple flat plate solar energy collector consists of an absorbing surface, painted usually in black to absorb insolation and transmit it to the working fluid (Ekechukwu & Norton, 1999, p. III). Meanwhile, Akhtar and Mullick (2007) concluded that solar energy collectors are special kinds of heat exchangers that transform solar radiation energy into internal energy of the transport medium, usually water or air. The solar energy collected is carried from the circulating fluid, either directly to the water or to the space conditioning equipment or to a thermal energy storage tank, which can be drawn for use at night or on cloudy days (Soteris, 2009). Generally, the flat-plate with more than one cover is used when high temperatures are required and a single cover is used when low temperatures are required (Akhtar & Mullick, 1999). Samdarshi and Mullick (1983, cited in Akhtar & Mullick, 1999) indicated that it was the best estimation of U_t, top loss coefficient in the literature, while Akhtar and Mullick (1999) compared their finding with that of Garg *et al.* (1983), where the percentage of error was found to be minimal. Akhtar and Mullick (1999) and Garg *et al.* (1983) concluded that the error in their findings was much lower than that of the previous findings, as a result of empirical relations use instead of numerical solutions.

Ho *et al.* (2009) investigated the effect of air recycling in double pass flat plate collectors with internal fins as heat sinks. An experimental investigation of three different types of solar air heaters adopting flat plates, two with fins attached, and others without fin was carried out by Alta et al. (2010). In their experiment, one of the heaters with fins had single glass cover, while the other with double. Based on the results, they concluded that the heater with double cover and fin was more efficient in terms of temperature difference of inlet and outlet air. Several other researchers concluded that flat plate collectors like V-grove, fin-air collectors, and chevron pattern absorbers as less efficient than the others. In their findings, El-sawi *et al.* (2010) concluded that putting the three patterns under the same conditions, the V-corrugated pattern was found to be more efficient than the others, with flat plate collector having the lowest performance.

The performances of flat plate collectors are affected by the climatic conditions of the test area or location. Sunshine time and intensity determine the efficiency of the plates. Other conditions such as dust, dirt, shadow, persistent rainfall are among the factors militating against their performances. The performances of the solar flat plate collectors are subject to location. In tropical regions where average daily sunshine can be up to 12 hours per day, better efficiencies are recorded compared to rain forests.

Types of Solar Energy Flat Plate Collectors

The solar energy flat plate collectors are basically divided into two broad classes, as follows:

- Bare-plate solar energy collectors
- Covered plate solar collectors

Bare-plate Solar Energy Collectors

These are the simplest of all solar collectors. The top-most surface is the absorber plate, with the rear insulated and an air duct, as presented by Ekechukwu and Norton (1999, p. III). Consider the following figure:

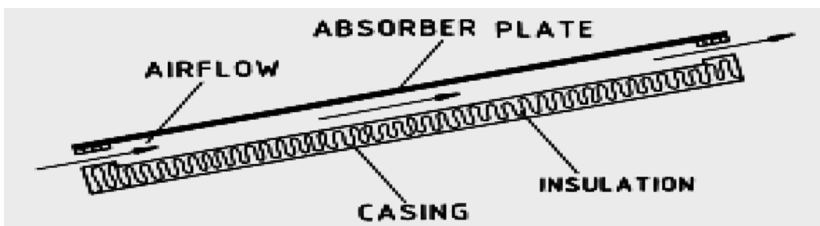

Fig.1: Bare plate solar collector (Ekechukwu & Norton, 1999, p. III)

They are commonly used in agricultural food drying. Optical loss which is caused by transmission reduction of incoming solar radiation, as a result of passing through the transparent cover, is about 10% of the insolation (Soddah *et al.,* 1982).

Covered Plate Solar Collector

Using one or more transparent cover materials minimizes the upward heat loss from the collectors (Ekechukwu & Norton, 1999, p. III). Glass, clear plastics and plexi-glass are identified as the most common materials used but glass material has gained more acceptance. The cover material, in addition to being transparent to allow direct falling of solar insolation to the plate, also prevents convective heat loss and plate against cooling especially during rain, and reduces long-wave radioactive heat losses. This is an advantage to the covered plate as it operates at higher efficiency than the bear plate (Ekechukwu & Norton, 1999, p. III). Ekechukwu and Norton (1999, p. III) describe four different types of covered plate solar heaters. The following schematic diagram is self-explanatory.

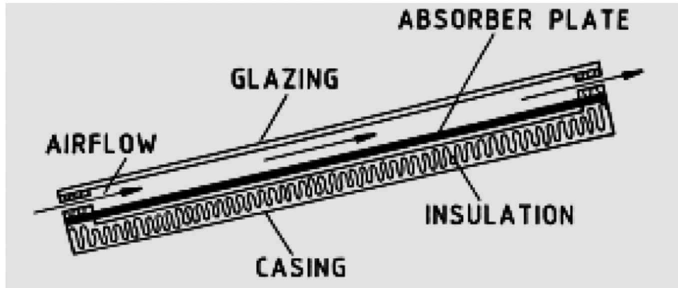

Fig.2: Front pass solar collector

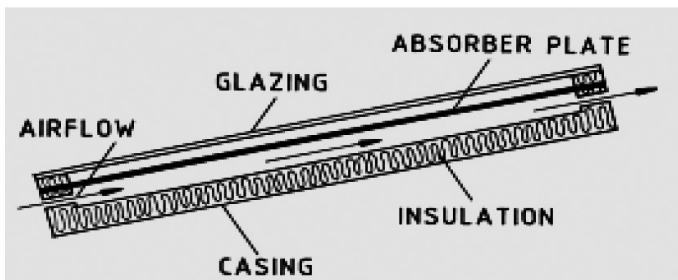

Fig.3: Back pass solar collector

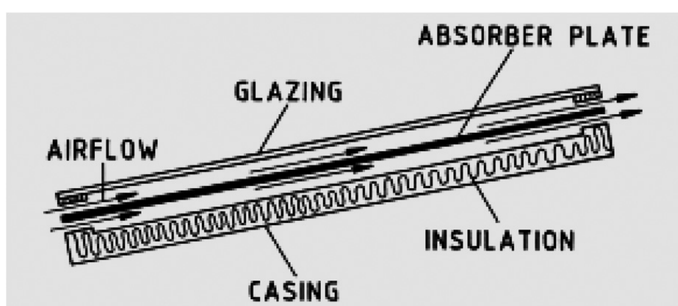

Fig.4: Parallel pass suspended solar plate collector (Ekechukwu & Norton, 1999, p. III)

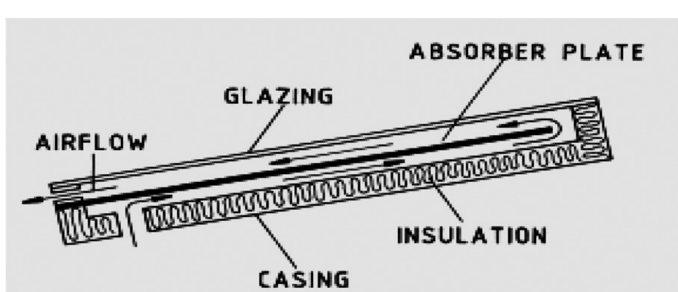

Fig.5: Double pass suspended solar collector

Solar Collectors in Cooling of Buildings

Many researchers have agreed that for solar cooling, the following guides are adoptable and acceptable (Rai, 1984; Tabor, 1966; Baker *et al.*, 1976):

1. Optimal collector area is greater than the area needed for heating only.
2. Two glass covers are optimum for sub-tropical climate; otherwise, three glass covers are desirable due to higher temperature requirement for the cooling system.
3. Optimal collector tilt, (O_T) is equal to latitude (φ), (except in south, where $O_T = \varphi - 10^0$)

Cold storage offers certain advantages over hot storage. The temperature difference ΔT between cold storage and the temperature of a building is less than the temperature difference ΔT between hot storage and building temperature. Thus, less cooling effect is lost from cold storage than from hot storage. This is adopted either to provide cooling for food preservation or for conform cooling. These can be done through refrigeration or evaporation processes.

Solar Collector in Heating of Buildings

The amount of heat to be supplied by solar conventional heater must equal the sum of heat loss through walls, the amount of heat required to warm ventilating air, and air entering through infiltration. If Q cubic meter per hour of air is introduced by ventilation and infiltration, the heat required to bring this air to room temperature is (Sodha *et al.*, 1985; Malik *et al.,* 1982):

$$q_v = Q \bullet C_p \rho (T_{in} - T_{out}) \quad \text{Kcal/hr} \tag{1}$$

C_p = Specific heat of air Kcal/Kg^{o}C
ρ = Density of air Kg/m^3
T_{in} = Room temperature (^{o}C)
T_{out} = Outside temperature (^{o}C)

Heat losses through structures on hourly basis are usually based on steady heat conditions. The rate of heat loss through a wall, a window or a ceiling in a steady state is given by:

$$q_{wall} = UA(T_{in} - T_{out}) \tag{2}$$

As U is an overall heat transfer coefficient, the total heat loss on a house is:

$$q_{total} = q_v + q_{wall} \tag{3}$$

The important parameters to be considered in the design of solar collector are collector tilt, number of covers and area of the collectors. Studies have shown that the optimum collector tilt to deliver each unit of heating at a minimum cost is approximately latitude + 15^o for hot services water heating required throughout the year. The optimum tilt is equal to the latitude. The most favourable orientation of the collector is facing south. The optimum number of glass covers varies with climate.

Performance of Collectors in Solar Air-heaters

The performance of solar air heater is given by the overall efficiency. Derivation of performance equations based on heat transfer model is presented in this subsection. Useful energy gain can be given as follows (Rai, 1984):

$$Q_u = \dot{m}c_p(T_o - T_i) \tag{4}$$

Under steady-state conditions, heat balance equation thus;

$$Q_u = AF_R I(\tau\alpha)_e - AF_R U_L(T_i - T_a) \tag{5}$$

A combination of factor, effective transmissivity, absorptivity product (τα) defines the ratio of solar radiation absorbed by the absorber plate to the incident solar flux (Rai, 1984; Malik *et al.,* 1982).

$$(\tau\alpha)_e = \tau\alpha + a[F_1 + F_2 + F_3 + \ldots + F_n] \tag{6}$$

Where, τα is the fraction transmitted by the cover plates and absorbed by absorbing plate, while F_1 , F_2 and F_3 are the fractions absorbed by each glass cover.

Instantaneous efficiency of the collector can be obtained from the following (Rai, 1984; Malik *et al.,* 1982):

$$\eta = F_R\left[(\tau\alpha) - U_L\frac{(T_i - T_a)}{I}\right] \tag{7}$$

$$\eta = \frac{Q_u}{IA} \tag{8}$$

The efficiency, η, is plotted against $(T_i - T_a)/I$. A single generalized curve represents the collector performance. Thus, various cover arrangements and/or selective coatings could be compared, as shown in Fig.6 below (Ekechukwu & Norton, 1999, p. III).

It is generally assumed that U_L is constant and the plot above is linear, as confirmed by Ekechukwu and Norton (1999, p. III), Rai (1984) and Tawari *et al*. (1991). This is true for small values of $(T_i – T_a)$, when the radiation loss is a small fraction of the total heat loss. At high values of $(T_i – T_a)$, the radiation loss predominates over convection and conduction losses as it is proportional to T^4_1. U_L has a positive but minimal value at $T_1 = T_a$. It increases with the increase in the value of T_1 or plate temperature and has a maximum value at the equilibrium plate temperature [9].

As for the test procedures, the value of Q_U is calculated from equation 1, but solar insulation, I, ambient and inlet temperature of fluid T_a and T_i are measured under assumed steady state conditions (Tawari *et al*., 1991). Duffie and Beckman (1980) concluded that long-term experiences on the performance of solar energy collectors showed that intercepts and slopes are good enough to characterize them.

Works have been carried out by many researchers world over on single and double pass solar air heaters. Double pass solar air heaters have a single glass cover but a double air-way

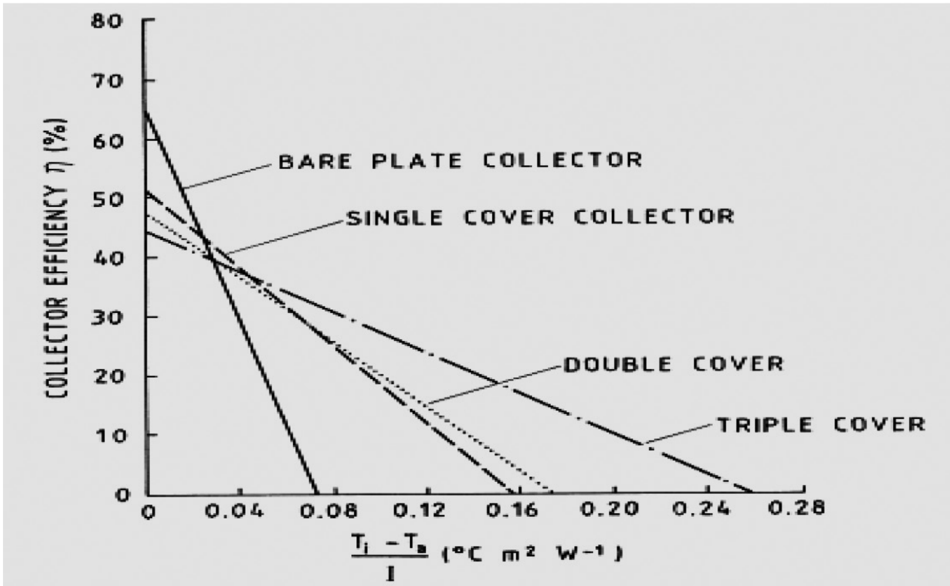

Fig.6: Performance curve for solar collectors

through which air passes at inlet at low temperature and at exit at high temperature. Air initially passes between the glass and absorber plate and then between the absorber plate and the bottom cover. This process has been found to enhance heat generation (see Ong, 1995; Hegazy, 2000; Naphon & Kongtragol, 2003; Aboul *et al.,* 2000; Hegazy, 1999). Other researchers like Choudhury *et al.* (1995) and Yeh *et al.* (2000) found that the increase in velocity of air increased the heat transfer coefficient, resulting in improved performance. Similarly, Sebaii (2011) also stated that to increase fluid velocity, recycling of air would produce the effect of remixing the inlet fluid with the outgoing fluid.

It is vital for all solar thermal systems to be able to store maximum energy for a working period so as to conserve energy in the flat plate collector box since most energy losses are through glass or plastic compared to walls, if good insulation is made to the walls and bottom of the collector (Abhishek *et al.*, 2011).

The performance of solar air heaters is given by overall efficiency as in the case of a flat-plate collector. The derivation of performance equations of the most popular solar air heater design, the flat-plate with air flow on one side based on the heat transfer model is presented by Rai (1984). Effective transmissivity determination for a given transparent cover combination is identical to that of a liquid heater. Effective transmissivity-absorptivity product (τα), which defines the ratio of solar radiation absorbed by the absorber plate to the incident solar flux $(\tau\alpha)_e$, can be calculated from:

$$(\tau\alpha) = \tau\alpha + a(A_1 + A_2 + A_3 + \ldots) \quad (9)$$

where τα is the fraction transmitted by cover plates and absorbed by the absorbing plate and A_1, A_2 the fraction absorbed by each glass cover.

The flux on the absorber can be computed by the term HR $(\tau\alpha)_e$ and heat losses by U_L $(T_p$-$T_a)$.
Heat balance on the absorber plate:

$$HR(\tau\alpha)_e(D\delta x) = U_L(D\delta x)(T_p + T_a) + h_c(D\delta x)(T_p - T) + h_r\varepsilon(D\delta x)(T_p + T_b) \tag{10}$$

D is the width, T_b is the bottom temperature
But ($U_L \sim U_{UP}$)
Heat balance on the air stream (control volume) is given by:

$$\dot{m}C_p\left(\frac{dT}{\delta X}\right)\delta x = h_c(D\delta x)(T_p - T) + h_c^I(B\delta x)(T_b - T) \tag{11}$$

where $\dot{m}$ is the mass flow rate.
Heat balance on the rear plate is obtained as:

$$h_r\varepsilon(D\delta x)(T_p + T_b) = h_c(D\delta x)(T_b - T) + U_b D\delta x(T_b - T_a) \tag{12}$$

The solution to these simultaneous equations yields a differential equation which defines the temperature variation of the air stream.

$$\dot{m}\frac{C_p}{D}\left(\frac{dT}{dx}\right) = \left[\frac{1}{1 + \frac{U_L}{h}}\right]\left[HR(\tau\alpha)_e - U_L(T - T_\alpha)\right] \tag{13}$$

$$h = h_C + \frac{1}{\frac{1}{h_C^I} + \frac{1}{\varepsilon h_r}} \qquad \text{as} \quad (U_b << U_L) \tag{14}$$

Letting $F^I = \frac{1}{1 + \frac{U_L}{h}}$ and solving the differential equation, the air temperature, T, at a distance x from the inlet end of the collector is found to be:

$$T = \frac{HR(\tau\alpha)_e}{U_L} - (T_1 - T_\alpha) + \frac{HR(\tau\alpha)_e}{U_L}\exp\left(\frac{-DF^I U_L x}{\dot{m}C_p}\right) + T_a \tag{15}$$

T_1 is the air inlet temperature:

$$T = \frac{S}{U_L} - T_1 + T_a + S\frac{S}{U_L}\exp\left(\frac{-DF^I U_L x}{\dot{m}C_p}\right) + T_a \tag{16}$$

The air temperature at the collector exists at a distance L is:

$$T_2 = T_1 + \left\{\frac{S}{U_L} - (T_1 - T_a)\left[1 - Exp\left(-F^I\frac{U_L}{GC_p}\right)\right]\right\} \tag{17}$$

G is the mass flow rate per unit area.

The overall heat transfer coefficient between the air stream and outside air through the transparent cover U_O is given by:

$$U_O = F^I U_L = \left(\frac{1}{\frac{1}{U_L} + \frac{1}{h}} \right) \quad (18)$$

Under ideal conditions, i.e. where the heat transfer from the absorber plate to the air stream is perfect;

$$h = \infty,\ F^I = 1, \text{ and } U_O = U_L \quad (19)$$

Substituting $F^I = U_o / U_L$, the heat picked up by the air stream is found to be:

$$\frac{Q_u}{A_c} = GC_V(T_2 - T_1) = \left(\frac{1}{1 + \frac{U_L}{h}} \right) \left[\frac{1 - Exp\left(-U_o / GC_p \right)}{U_o / GC_p} \right] x \left[S - U_L(T_1 - T_a) \right] \quad (20)$$

In terms of flow factors, F^{II}, the equation is reduced to

$$\frac{Q_U}{A_C} = F^I F^{II} \left[S - U_L(T_1 - T_o) \right] \quad (21)$$

$$q = F_R \left[S - U_L(T_1 - T_o) \right] \quad (22)$$

Thus, $F^I = \frac{F_R}{F^{II}}$

From equation 22 above, we see that efficiency is increased by increasing F' and F'', $(\tau\alpha)_e$ and reducing U_L. U_L and $(\tau\alpha)_e$ are related to the characteristics of the upper surface of the absorber plate and the transparent cover system. F' and F'' can be increased by increasing the mass flow rate per unit area G and in the convective heat transfer coefficient between the air stream and the absorber plate, as well as increasing surface to transfer heat from the absorber plate to the air stream using fins.

The threshold level is defined by

$$(H_C R) = U_L \frac{(T_1 - T_a)}{\tau\alpha_e} \quad (23)$$

(H_cR) denotes the critical radiation intensity.
The usual heat collected is therefore expressed with a linear relation of

$$\frac{Q_u}{A_c} = C(HR) - K(T_1 - T_a), \qquad HR \geq P(H_c R) \quad (24)$$

$$C = F' F'' (\tau\alpha)_e$$

$$K = F' F'' (U_L)$$

The solar air heaters efficiency must be defined as:

$$\eta = \frac{Q_u}{A_c(HR)} = \frac{q_u}{(HR)} \tag{25}$$

Performance of Collectors in Water Heating

Many different designs of collectors have been experimented on and are basically on insulated box with one or more transparent covers, containing a black painted metal absorber plate and some arrangements for circulating water pass the plate. The flat-plate collectors that are most commonly used are shown schematically below (Rai, 1984; Sheffer, 1994; Rosenbaum, 1991).

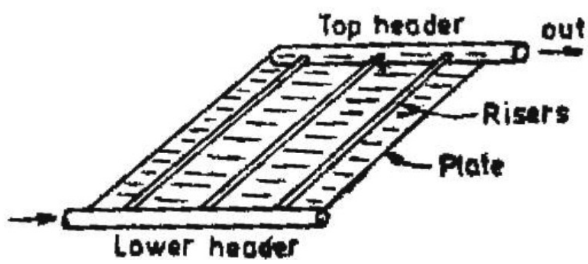

Fig.7: A schematic view of a ‘conventional’ solar water heater collector plate

The absorber typically uses parallel 1.2 to 1.5 cm diameter tubes, place about 12 to 15 cm apart, soldered or brazed into headers of about 2.5 cm in diameter at the top and the bottom and the tubes are soldered to the plates. Another type has a long continuous tube bent in a sinusoidal shape rather than parallel tubes, and plates formed of one flat and one corrugated sheet fastened together to form water passages (Lawand *et al.,* 1966).

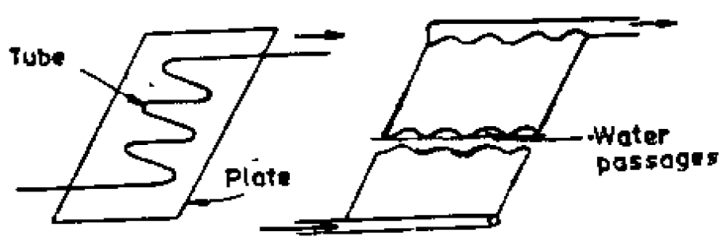

Fig.8: Alternative solar water heater collector plates

Several basic constructional differences are available for the absorber plates and the principal aim is to achieve the following:

- Inexpensive unit that is leak proof and reliable
- Efficient means of transferring heat quickly and evenly to water flow
- Steady and uniform distribution of water
- Maximum energy absorbing surface

Among the common materials used for absorber plates are copper and aluminium, apart from galvanized iron. The absorber plates are mounted in a metal or absorber plates with 5 to 10 cm of insulation behind the plates and 2.5 cm air gaps. It is usually coated with a substance that enhances its absorbing ability. The simplest and cheapest but ideal one is called selective black paint for higher absorption and low emissivity to minimize re-radiation of energy. The most commonly used transparent cover is glass. It is easily available and has good transmittance but it may be expensive, heavy and brittle.

SOLAR DRYING

Food is a basic need for all living things, in addition to air and water. Food shortages arise in most developing and under developed countries around the globe as a result mostly of their inability to preserve food rather than producing it. Agricultural produce are always in excess of immediate consumption, and therefore storage and/or processing becomes imperative. In developing countries, more than 80% of the production is by small scale farmers (Murphy, 2009).

Drying is quite a simple ancient skill. It is one of the easily accessible and widely used processing technologies (Jairaj *et al.,* 2009). Drying is a dual process of:

- Heat transfers to the product from the heating source
- Mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air (Ekechukwu & Norton, 1999, p. II)

Solar energy is used either as the main source of heat or as a supplementary source. Agricultural produce are dried in different ways.

1. In direct type drying, produce are exposed to solar radiation or a combination of solar radiation and reflected radiation;
2. In indirect type of solar dryers, produce are NOT exposed directly but are air heated by solar radiation; the air heated by solar radiation is made to pass though them.
3. In the mixed type solar dryer, produce are exposed directly to solar radiation with pre-heated air flowing through.
4. In natural circulation mode, air is heated from different points and made to pass through the produce by buoyancy force or as a result of wind pressure or both.
5. In forced circulation mode, heated air is circulated through the produce by a motorized air blower that is powered by another source, which is probably by conventional electricity or by solar power.

All drying systems can be classified primarily according to operating temperature ranges in two main groups; high and low temperature dryers (Ekechukwu & Norton, 1999, p. I). It is generally accepted that high temperature dryers are powered by fossil fuels and low temperature by solar energy. Solar energy drying systems are schematically classified as shown in Fig.9 below (Ekechukwu & Norton, 1999, p. I).

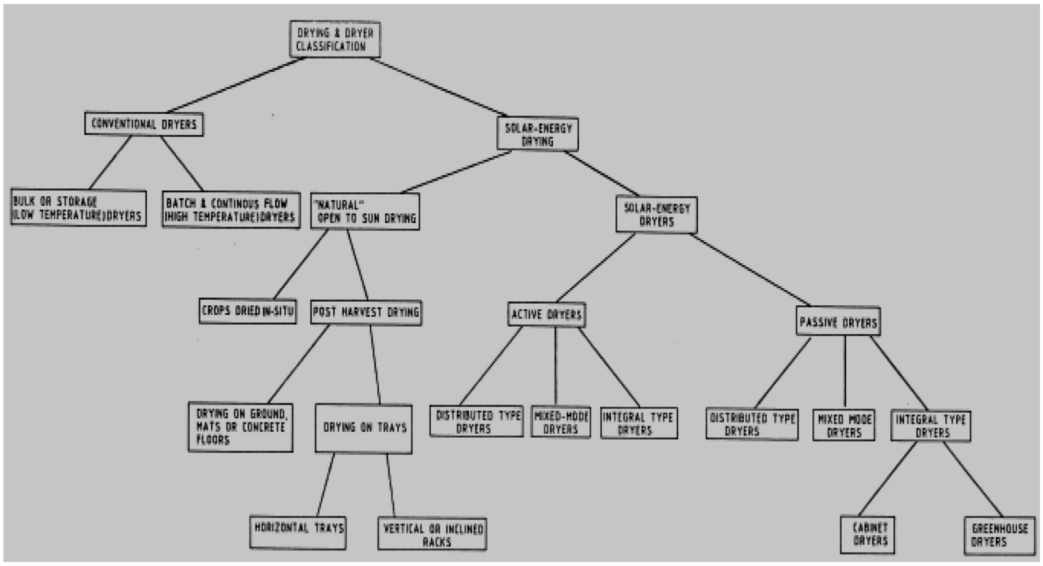

Fig.9: Classification of dryers and drying modes

Fig.9 illustrates a schematic classification of dryers. The concept of three similar classifications under active and passive methods is also schematically shown in Fig.10 (Ekechukwu & Norton, 1999, p. I). In order to further classify the drying methods, various types of solar dryers are identified and schematically presented by Jairaj *et al.* (2009). These include the following:

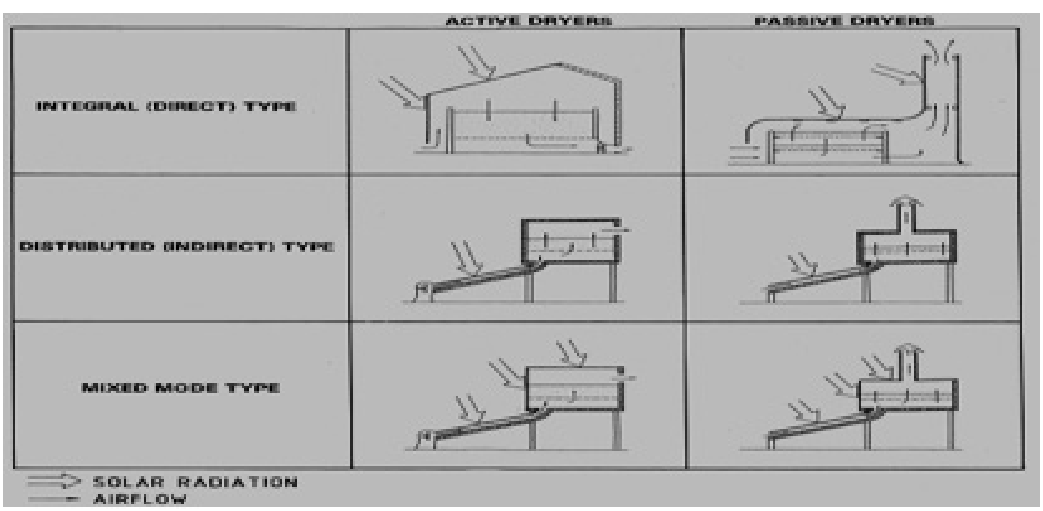

Fig.10: A typical solar energy dryer design

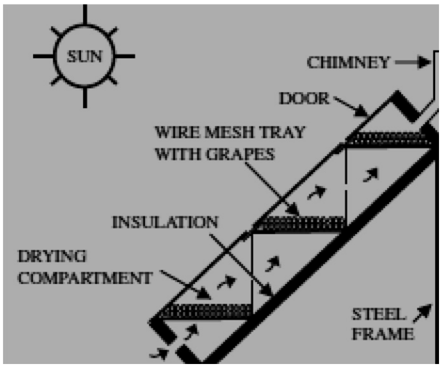

Fig.11: Stair case dryer

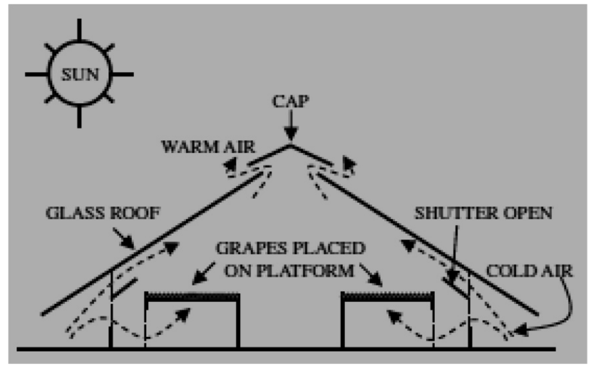

Fig.12: Glass roof solar dryer

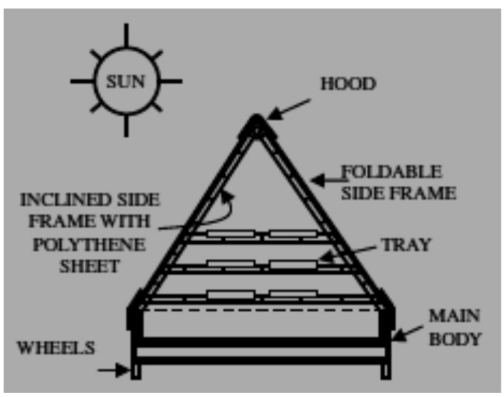

Fig.13: Foldable dryer

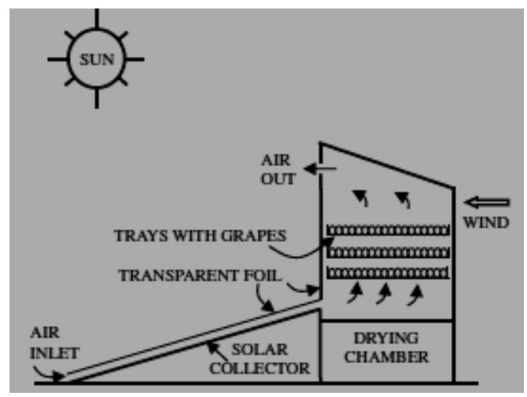

Fig.14: Indirect type of conventional solar dryer

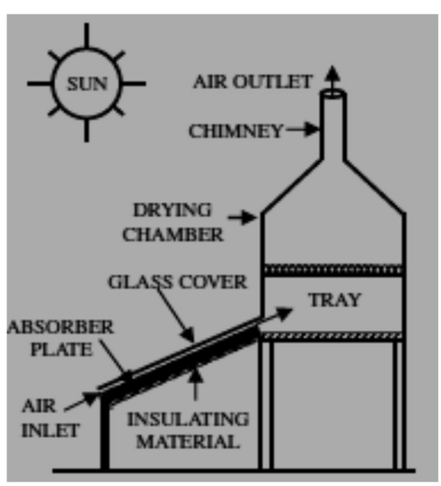

Fig.15: Indirect natural conventional dryer
with chimney

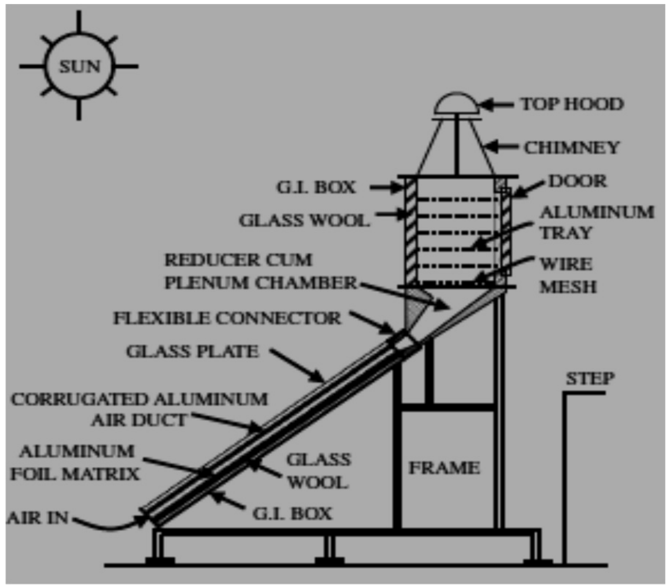

Fig.16: Multipurpose natural convention dryer

Karsli (2007, as cited in Sebali & Shalaby, 2011) made a comparative study of four types of air heating flat-plate collectors: a finned collector with an angle of 75°, a finned collector with an angle of 70°, a collector with tubes and a base collector. He concluded that their efficiency depended significantly on solar radiation, and surface geometry of the collectors and that the overall loss is lower at higher reduced temperature parameter.

Fudholi *et al.* (2010) carried out comparative studies between direct and indirect cabinet dryers. The result tilted in favour of the direct solar dryer. They found that 70% of humidity in pepper was removed within 72 hrs using a direct cabinet dryer compared to within 243 hrs using an indirect one. The mathematical modelling presented by the authors was to put models that describe drying kinetics, and thus:

The first exponential model was in the form of

$$Xr(t) = A_0 + A_1 \exp(-bt) \tag{26}$$

The A and b are functions of drying conditions.
The second proposed model was in the form;

$$Xr(t) = \exp(-\sqrt{kt}) \tag{27}$$

K is the coefficient, a function of drying conditions.

Drying helps to reduce moisture content to a level where deterioration does not occur and dried products can be stored for a definite length of time. Various researchers have worked on testing the performances of different designed dryers, and results have been published by authors such as Klein (1975), Sharma *et al.* (1993) and Tiwari and Ghosa (2005).

Methods of Drying

Drying is the most common form of food preservation and way of extending shelf life of food (Sarasavadha *et al*., 1999). Water, a major constituent of fruit and food, is important in controlling the rates of deteriorative reaction including those resulting in nutrient losses (Sayul & Karel, 1980). This is done by lowering the moisture to a level where microorganisms cannot grow and reaction rates are slowed down (Mahmutoghu *et al.*, 1996).

At the start of drying in the first instance, the food to be dried is very moist or damp, and the moisture content is the same for the inside and outside of the food produce. Then, as the heating continues, with the water particles being taken away by the heating process, the surface of the product begins to dry. This is followed by the migration of water particles from the inside of the product to the surface via diffusion and the drying process continues. At this stage, the energy required for this process is much more important than the first condition, and this stage of drying is subject to type of product. Temperature influence at this stage is critical, as the maximum allowable temperature is about 20^0C in excess of the ambient temperature.

In the open sun drying process, solar radiation heat is used to evaporate the moisture present in the product. Since sunshine is intermittent and varies, the product may become over- or under dried [13]. Hence, solar energy is used to heat a large volume of air and this air flows over the product to remove and take away the moisture. However, hot air can be circulated again to save energy (McDoom *et al.,* 1999). Lack of uniform drying and inaccurate prediction of drying times are among the possible problems that are usually encountered in solar drying (Scheonal *et al.*, 1996). Equilibrium moisture level is defined as the moisture level when in equilibrium with the relative humidity of the environment (Bala, 1998; Klein, 1975).

Open Sun Drying without Cover

In this case, part of the solar radiation falls, penetrates and be absorbed by the material itself resulting in heat generation in the interior of the product as well as its surface, and thus generating heat transfer. Solar radiation absorptance-transmittance product is an important factor here. Generally, the agricultural produce in the dryer are, at intervals, rotated to expose the other parts to sun's radiation and ensure a uniform drying. The drying time length varies according to drying materials pending on the amount of water content of the produce; however, the environmental condition of dryer usage may affect the performance. Consider Fig.17 below for grapes drying (Jairaj *et al.,* 2009).

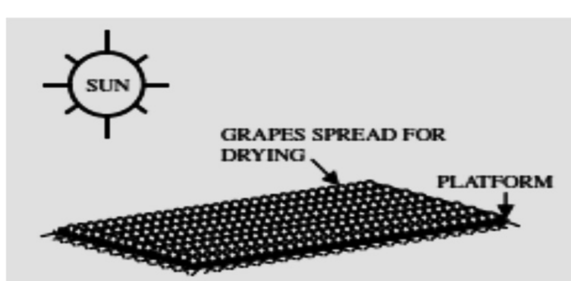

Fig.17: Open sun drying without cover

Open Sun Drying with Cover

A schematic view of open sun drying with plastic cover for grapes is shown in Fig.18 (Jairaj *et al.,* 2009). In this case, the plastic cover offers two services; as a heat trap and as a protective cover from contamination to a certain extent. Jairaj *et al.* (2009) found that the quality of produce from the grapes dried with cover is better than that from grapes with open sun drying.

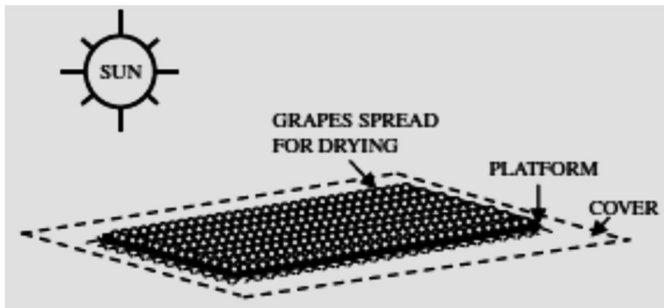

Fig.18: Open sun drying with cover

Natural Rack Drying

This is also another form of shade drying process. Fig.19 depicts a shade dryer. The dryer may consist of up to 10 shelves or more with a uniform spacing between each shelf. The orientation is such that the contents receive solar radiation in the morning and afternoon, while shaded at zenith angle with the shade provided by the roof. For grapes, the drying may take place in two weeks (Amba & Anand, 1972).

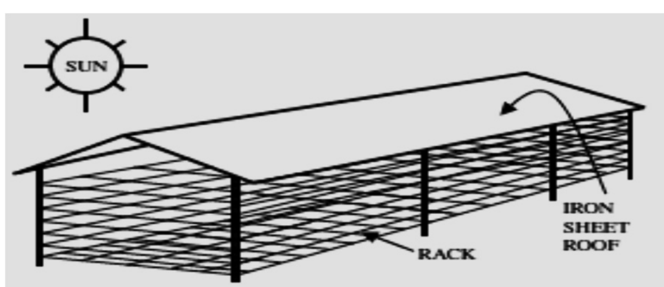

Fig.19: Natural rack dryer

OTHER APPLICATIONS OF FLAT PLATE COLLECTORS

Apart from the applications of the flat plate solar collectors discussed above, other applications include:

(a) Solar pond, in which a mass of shallow water about 1.5 – 2 metre deep, with a large collection area, acting as a heat trap. In such a pond, salt is added to maintain a stable density gradient. As solar incidence falls, it penetrates throughout the depth of the pond with its black bottom.

(b) Solar thermal power generation, in which solar energy is converted into thermal energy by flat plate or concentrating collectors. Thermal energy generated is used to drive heat engine.

(c) Solar furnaces, in which large amount of heat energy is generated by concentrating solar radiation onto a specimen. In this case, flat plate collectors are utilized to boost energy generation.

(d) Solar water pumping, which can be used for irrigation for drinking, either by animals or by humans. Flat plate is utilized to generate heat which is then used by a heat exchanger to power a heat engine that will in turn start a heat pump.

(e) Solar distillation, either for obtaining distilled water or for obtaining potable water from sea or salty water body. This is accomplished by exposing thin body of water to solar radiation and condensing the water vapour produced on a transparent cover so that it is collectable in a receiving trough. The thin layer of water lies on a flat plate collector.

(f) Solar cookers, in which the heat collected by the flat plate in the cooker box is transmitted to the food, with solar concentrator on the plate to boost heat generation.

CONCLUSION

A brief overview of the basic relations used in the analysis of solar collectors is presented in solar cooling and heating of buildings, air and water heating, and agricultural produce drying. Different types of flat-plate solar collector utilizations are enumerated. Meanwhile, types of agricultural product drying methods are presented in relation to specific products. Flat plate collectors are generally concluded to be less efficient than V-corrugated collectors, finned plate collectors, and chevron pattern collectors. However, flat plate collectors are suitable for low temperature applications. The overall heat loss coefficient determining the performance of flat-plate collectors and possible losses from top, bottom and sides have also been enumerated in the review.

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